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APGC-TDR-63-16

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**Study of Target Penetration
Prediction by High Speed and
Ultra High Speed Ballistic Impact
Fifth Quarterly Report**

(1 July 1962 - 30 September 1962)

APGC Technical Documentary Report No. APGC-TDR-63-16

MARCH 1963 • OAR Project 9860

DEPUTY FOR AEROSPACE SYSTEMS TEST

AIR PROVING GROUND CENTER

AIR FORCE SYSTEMS COMMAND • UNITED STATES AIR FORCE

EGLIN AIR FORCE BASE, FLORIDA

(Prepared under Contract No. AF 08(635)-2155 by Hayes
International Corporation, Research Section, Birmingham, Ala.)



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FOREWORD

This report was prepared under Air Force Contract Number AF 08(635)-2155, "Study of Target Penetration Prediction By High Speed and Ultra High Speed Ballistic Impact." Work was administered under the direction of APGC (PGWRT), Eglin Air Force Base, Florida, with Mr. A. G. Bilek as Project Engineer.

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ABSTRACT

The main effort during this report period has been directed toward "cleaning up" the empirical data used in the statistical analyses. An analysis of 1,034 shots divided into 768 "high" velocity shots and 266 "low" velocity shots shows that about 90% of the variation in penetration depth may be explained by a simple power law formula utilizing four or five independent variables including a target strength parameter.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.


MORRILL E. MARSTON
Colonel, USAF
Deputy for Aerospace Systems Test

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LIST OF SYMBOLS

| | |
|--------|--|
| c | - dilatational wave velocity |
| D_p | - projectile diameter |
| e | - tensile elongation |
| H | - Brinell hardness |
| K | - bulk modulus |
| P_c | - crater depth measured from original target surface |
| S | - shear strength |
| V | - volume |
| v | - impact velocity |
| ρ | - mass density |

SUBSCRIPTS

| | |
|-----|--------------|
| c | - crater |
| p | - projectile |
| t | - target |

INTRODUCTION

The purpose of this study is to gather and assemble existing data on ballistic impact and on material failure, especially at high impact velocities or large loading - to establish the relative importance of such factors as projectile velocity, mass, projectile-target strengths, ductilities, densities, compressibilities, etc., and to use this information to deduce the mathematical relationships of critical factors as the target structure responds to impact and is penetrated.

Existing experimental data relative to ballistic impact at high velocities are being analyzed on a statistical basis through the use of a digital computer. The general form of the statistical approach was outlined in the First Quarterly Report.¹ A preliminary analysis of the correlation between depth of penetration and ten independent variables was reported in the Second Quarterly Report² and discussed more fully in the Third Quarterly Report³. In the Fourth Quarterly Report⁴, 1,275 experimental shots were divided into two groups, according to whether the impact velocity lay below or above the bulk wave velocity in the target material. Separate analyses of the two groups showed interesting relationships with existing theoretical and experimental equations.

In addition, the general areas of ballistic impact and material failure are being investigated in order to develop relationships which may be tested against existing experimental data. Some general aspects of target behavior under ballistic impact were discussed in the Second Quarterly Report, and some justification was given for the use of static or quasi-static material parameters in the initial statistical analysis. Initial attempts to formulate a theoretical model for the purpose of testing accumulated experimental data were outlined in the Third Quarterly Report. In the Fourth Quarterly Report, a semi-rational penetration expression was developed which suggests that the nonrecoverable target compression and shear strain energies may account for most of the projectile kinetic energy.

EMPIRICAL MODEL

Both the "high" and the "low" velocity sets of data which were used in the previous progress report to evaluate the k_1 in equations of the form

$$P_c / v_p^{1/3} = k_0 v^{k_1} t^{k_2} p^{k_3} \dots$$

have been "cleaned up" according to the method previously outlined. The equation

$$P_c/D_p = 8.43 \times 10^{-3} v^{1.06} \rho_t^{-.365} \rho_p^{.984} S_t^{.400} T_t^{.586} e_t^{.010} v_p^{.035} C_t^{.252}$$

which was taken from Table III of the previous progress report, was used to calculate the depth of penetration for each of the "low" velocity shots. The calculated penetration depth was compared with the measured penetration depth and a per cent error was calculated. All shots with an error greater than 50% were then scrutinized in an effort to spot recording or computer errors. In addition, the small number of shots in which the temperature of the target or the impact angle were other than ambient and 90° , respectively, were eliminated.

After "cleaning", a total of 1,034 shots remained, of which 768 are classified as "low" velocity and 266 are classified as "high" velocity. Since it is possible to prove almost any result by the indiscriminate omission of conflicting data, the elimination of data must be analyzed quite seriously. A careful breakdown of all data eliminated and plots of the new distributions of target materials as a function of impact velocity will be given in the next progress report. However, the final results of four runs on each of the new "high" and "low" velocity sets are shown in Tables 1 - 8.

The multiple correlation coefficients in Tables 1 - 8 show that using four independent variables (ie: v , ρ_p , S_t , and ρ_t) it is possible to explain 92% of the variation in penetration depth using the low velocity data and 87% of the variation in penetration depth using the high velocity data.

The general conclusions made in the previous progress report apply to Tables 1 - 8 with the major exceptions that penetrations show a high velocity dependence on ρ_p closer to $2/3$ than $1/3$ and that the role of ρ_t appears more well defined. A more complete discussion of results will be postponed until the next report.

Future work will be pointed toward the use of the "cleaned up" data to check the equations developed under the present contract and to test other theories and empirical equations.

Table I. "Low" Velocity Data Evaluation of the Coefficients k_i in the Equation

$$Pc/V_p^{1/3} = k_0 v^{k_1} \rho_p^{k_2} S_t^{k_3} \rho_t^{k_4} e_t^{k_5} K_t^{k_6} C_t^{k_7}$$

| k_0 | k_1 | k_2 | k_3 | k_4 | k_5 | k_6 | k_7 | Multiple Correlation Coefficient |
|-------|-------|-------|-------|-------|-------|-------|-------|--|
| .0118 | .879 | 1.01 | -.437 | -.326 | -.006 | -.036 | .335 | .934 |
| .125 | .897 | .977 | -.455 | -.350 | .036 | .009 | | .925 |
| .140 | .897 | .978 | -.450 | -.345 | .036 | | | .925 |
| .172 | .893 | .979 | -.457 | -.350 | | | | .925 |
| .189 | .840 | .915 | -.379 | | | | | .900 |
| .025 | .626 | .825 | | | | | | .725 |

Table 2. "Low" Velocity Data Evaluation of the Coefficients k_i in the Equation

| k_0 | $P_c/V_p^{1/3} = k_0 \cdot V_p^{k_1} \cdot \rho^{k_2} \cdot C_t^{k_3} \cdot \rho_t^{k_4} \cdot e_t^{k_5} \cdot K_t^{k_6} \cdot C_p^{k_7}$ | | | | | | | | | | Multiple Correlation Coefficient |
|-------|---|-------|-------|-------|-------|-------|-------|--|--|--|--|
| | k_1 | k_2 | k_3 | k_4 | k_5 | k_6 | k_7 | | | | |
| 3.41 | .816 | 1.03 | -2.27 | -1.18 | .192 | .557 | .415 | | | | .913 |
| 82.5 | .823 | .954 | -1.87 | -.983 | .259 | .373 | | | | | .899 |
| 92.3 | .829 | .976 | -1.19 | -.611 | .257 | | | | | | .898 |
| 1008 | .790 | .988 | -1.34 | -.677 | | | | | | | .893 |
| 14.9 | .708 | .866 | -.736 | | | | | | | | .830 |
| .025 | .626 | .825 | | | | | | | | | .725 |

Table 3. "Low" Velocity Data Evaluation of the Coefficients k_i in the Equation

$$P_c/V_p^{1/3} = k_0 v^{k_1} \rho_p^{k_2} H_t^{k_3} \rho_t^{k_4} e_t^{k_5} K_t^{k_6} C_p^{k_7}$$

| k_0 | k_1 | k_2 | k_3 | k_4 | k_5 | k_6 | k_7 | Multiple Correlation Coefficient |
|-------|-------|-------|-------|-------|-------|-------|-------|--|
| .0005 | .869 | 1.00 | -.443 | -.370 | -.090 | .004 | .325 | .932 |
| .005 | .887 | .976 | -.465 | -.400 | -.057 | .058 | | .924 |
| .013 | .883 | .978 | -.435 | -.371 | -.047 | | | .923 |
| .010 | .887 | .975 | -.426 | -.365 | | | | .923 |
| .019 | .832 | .909 | -.348 | | | | | .896 |
| .025 | .626 | .825 | | | | | | .725 |

Table 4. "Low" Velocity Data Evaluation of the Coefficients k_i in the Equation

| $P_c/V_p^{1/3} = k_0 v^{k_1} \rho_p^{k_2} (Se)_t^{k_3} \omega_t^{k_4} e_t^{k_5} K_t^{k_6} C_p^{k_7}$ | | | | | | | | | | Multiple Correlation Coefficient |
|--|-------|-------|-------|-------|-------|-------|-------|--|------|--|
| k_0 | k_1 | k_2 | k_3 | k_4 | k_5 | k_6 | k_7 | | | |
| .012 | .879 | 1.01 | -.437 | -.326 | -.443 | -.036 | .335 | | .934 | |
| .125 | .897 | .977 | -.455 | -.350 | -.419 | .010 | | | .925 | |
| .140 | .897 | .978 | -.450 | -.345 | -.414 | | | | .925 | |
| .020 | .919 | .955 | -.365 | -.287 | | | | | .918 | |
| .030 | .874 | .906 | -.317 | | | | | | .900 | |
| .025 | .626 | .825 | | | | | | | .725 | |

Table 3. "High" Velocity Data Evaluation of the Coefficients k_i in the Equation

| k_0 | $P_c/V_p^{1/3} = k_0 v^{k_1} \rho^{k_2} s_t^{k_3} \sigma^{k_4} e_t^{k_5} K_t^{k_6} C_p^{k_7}$ | | | | | | | Multiple Correlation Coefficient |
|-------|---|-------|-------|-------|-------|-------|-------|--|
| | k_1 | k_2 | k_3 | k_4 | k_5 | k_6 | k_7 | |
| .328 | .474 | .675 | -.362 | -.489 | -.123 | .117 | -.014 | .877 |
| .290 | .472 | .675 | -.362 | -.489 | -.122 | .117 | | .877 |
| 1.12 | .468 | .670 | -.300 | -.431 | -.103 | | | .875 |
| .772 | .449 | .673 | -.275 | -.426 | | | | .874 |
| .108 | .658 | .546 | -.235 | | | | | .817 |
| .565 | .268 | .612 | | | | | | .644 |

Table 6. "High" Velocity Data Evaluation of the Coefficients k_i in the Equation

| $P_c/V_p^{1/3} = k_0 v^{k_1} \rho^{k_2} C_t^{k_3} \rho_t^{k_4} e_t^{k_5} K_t^{k_6} C_p^{k_7}$ | | | | | | | | | |
|---|-------|-------|-------|-------|-------|-------|-------|--|--|
| k_0 | k_1 | k_2 | k_3 | k_4 | k_5 | k_6 | k_7 | Multiple Correlation Coefficient | |
| 35.2 | .364 | .721 | -1.43 | -.993 | .157 | .404 | .013 | .851 | |
| 39.8 | .364 | .720 | -1.43 | -.993 | .156 | .405 | | .851 | |
| 61.4 | .371 | .689 | -.729 | -.597 | .137 | | | .845 | |
| 190 | .383 | .686 | -.821 | -.623 | | | | .841 | |
| 2.58 | .580 | .534 | -.494 | | | | | .738 | |
| .565 | .268 | .612 | | | | | | .644 | |

Table 7. "High" Velocity Data Evaluation of the Coefficients k_i in the Equation

| $P_c/V_p^{1/3} = k_0 + k_1 \rho_p + k_2 H_t + k_3 \rho_t + k_4 e_t + k_5 K_t + k_6 C_p + k_7$ | | | | | | | | | |
|---|-------|-------|-------|-------|-------|-------|-------|----------------------------------|--|
| k_0 | k_1 | k_2 | k_3 | k_4 | k_5 | k_6 | k_7 | Multiple Correlation Coefficient | |
| .017 | .464 | .432 | -.365 | -.558 | -.097 | .167 | -.019 | .875 | |
| .014 | .463 | .684 | -.364 | -.558 | -.096 | .166 | | .875 | |
| .169 | .456 | .675 | -.278 | -.463 | -.071 | | | .872 | |
| .146 | .443 | .677 | -.262 | -.458 | | | | .871 | |
| .025 | .656 | .543 | -.215 | | | | | .806 | |
| .565 | .268 | .612 | | | | | | .644 | |

Table 8. "High" Velocity Data Evaluation of the Coefficients k_i in the Equation

| $P_c/v_p^{1/3} = k_0 v^{k_1} \rho_p^{k_2} (Se)_t^{k_3} \rho_t^{k_4} c_t^{k_5} K_t^{k_6} c_p^{k_7}$ | | | | | | | | | |
|--|-------|-------|-------|-------|-------|-------|-------|--|--|
| k_0 | k_1 | k_2 | k_3 | k_4 | k_5 | k_6 | k_7 | Multiple Correlation Coefficient | |
| .328 | .473 | .674 | -.362 | -.489 | .239 | .117 | .014 | .877 | |
| .291 | .473 | .675 | -.362 | -.489 | .240 | .117 | | .877 | |
| 1.12 | .468 | .670 | -.300 | -.431 | .197 | | | .875 | |
| 2.81 | .486 | .663 | -.340 | -.426 | | | | .865 | |
| .326 | .687 | .537 | -.288 | | | | | .808 | |
| .565 | .268 | .612 | | | | | | .644 | |

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